

TITLE OF THE INVENTION  
NONVOLATILE SEMICONDUCTOR MEMORY DEVICE AND DATA  
PROGRAM METHOD THEREOF

CROSS-REFERENCE TO RELATED APPLICATIONS

5           This application is based upon and claims the  
benefit of priority from the prior Japanese Patent  
Application No. 2002-347799, filed November 29, 2002,  
the entire contents of which are incorporated herein by  
reference.

10                           BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a nonvolatile  
semiconductor memory device and a method of programming  
data into the nonvolatile semiconductor memory device.

15           2. Description of the Related Art

An electrical connection diagram of a typical NAND  
EEPROM is shown in FIG. 1. The NAND EEPROM includes  
NAND cells as memory cells. The NAND cell is  
configured by serially connecting cell transistors with  
20 the sources of the cell transistors respectively  
connected to the drains of the adjacent cell  
transistors. In the NAND cell, since the adjacent cell  
transistors commonly use the source and drain, the  
number of contacts between the cells and bit lines can  
25 be reduced and it is suitable for high integration.  
Further, since the gates of a large number of cell  
transistors are simultaneously driven via a word line

WL, data can be programmed into or read out from a large number of cell transistors at high speed.

On the other hand, in the NAND EEPROM, all of the non-selected cell transistors in the NAND cell must be  
5 turned ON in order to read out data from a selected cell transistor. Therefore, the threshold voltage of each cell transistor is controlled to be set within a preset range. For example, if the threshold voltage is excessively low, the cell transistor cannot be  
10 separated from the non-programmed cell. However, if the threshold voltage is excessively high, the cell transistor cannot be turned ON when it is used as a non-selected cell.

As one example of a method for controlling the  
15 threshold voltage of the cell transistor, the flow of a programming method with the verify operation is shown in FIG. 2. After the program operation is performed by applying program gate potential ( $V_{pgm}$ ) to the word line WL, the readout operation is performed by applying  
20 verify readout gate potential ( $V_{verify}$ ) to the word line WL. At this time, sufficiently high readout gate potential ( $V_{read}$ ) is applied to the non-selected word lines WL which are not used for data programming to set the non-selected cell transistors in the ON state. In  
25 this state, when the selected cell transistor is turned ON, it is determined that the threshold voltage of the cell transistor is excessively low, that is, a

programmed amount is insufficient. Then,  $V_{pgm}$  is raised by a preset amount ( $\Delta V_{pgm}$ ) and a next program operation is performed. The above technique is called a step-up program technique and described in documents 1 to 3, for example. On the other hand, when the selected cell transistor is turned OFF, it can be determined that the threshold voltage of the cell transistor is made sufficiently high and the program operation is terminated. Since the actual program operation is simultaneously performed for a large number of cell transistors via a word line WL, termination of the program operation indicates that the operation mode is changed into a program inhibition state which will be described later.

FIG. 3 shows an example of a time chart at the data programming time of the NAND EEPROM. In FIG. 3, the names of respective nodes correspond to those of FIG. 1. Assume that the bit line BLk in FIG. 1 is used as a program bit line and the bit lines BLk+1, BLk-1 are used as program suppression bit lines. At the program time, preset gate potential ( $V_{sg}$ ) is applied to the gate of a selection transistor SG1 on the bit line side. Then, sufficiently low potential ( $V_{BLpgm}$ ) is applied to the bit line BLk used for programming.  $V_{sg}$  is set to such potential with respect to  $V_{BLpgm}$  as to sufficiently turn ON the selection transistor SG1. Further, sufficiently high potential ( $V_{BLinhibit}$ ) is

applied to the bit lines BLk+1, BLk-1 used to inhibit the program operation. VBLinhibit is set to such potential as to sufficiently turn OFF the selection transistor SG1. When VBLpgm is applied to the bit  
5 line, the selection transistor SG1 is turned ON to transmit VBLpgm to the cell transistor to sufficiently lower the channel potential of the cell transistor so that the program operation can be performed. When VBLinhibit is applied to the bit line BL, the selection  
10 transistor SG1 is turned OFF and the channel potential of the cell transistor is not lowered so that the program operation cannot be performed. This state is the program inhibition state.

At the first program time, after VBLpgm is applied  
15 to the bit line BLk connected to the cell transistor to be programmed and VBLinhibit is applied to the bit lines BLk+1, BLk-1 connected to the cell transistors which are inhibited from being programmed, Vpgm is applied to the word line WL. Next, after the bit line  
20 BL is charged to preset initial charged potential, Vverify is applied to the word line WL to perform the verify readout operation. When the cell transistor is turned ON and the bit line BL is discharged, a programmed data amount is insufficient, and therefore,  
25 the program operation is performed in a next program process. When the cell transistor is turned OFF and the bit line BL is not discharged, a programmed data

amount is sufficient, and therefore, the potential of the bit line BL is set to  $V_{BLinhibit}$  to set up the program inhibition state in a next program process. The potential of the word line WL is increased to

5  $V_{pgm} + \Delta V_{pgm}$  to perform an additional program operation with respect to the cell transistor which is determined to have an insufficient programmed data amount. Thus, the verify operation for the threshold voltage of the cell transistor is performed after the program

10 operation and the control operation is performed to determine whether the program operation is performed or inhibited in the next program process based on the result of the verify operation. The above operations are repeatedly performed until the program operations

15 for all of the cell transistors are terminated while the potential of the word line WL is gradually increased. As a result, the threshold voltage of the cell transistor is controlled to be set within a desired range. That is, the lowest threshold voltage

20 of the cell transistor is set to  $V_{verify}$  and the threshold voltage distribution range obtained after the end of the program operation is determined by  $\Delta V_{pgm}$ . Therefore, if  $V_{verify}$  is set sufficiently high with respect to the cell which is not to be programmed and

25  $V_{verify} + \Delta V_{pgm}$  is set sufficiently low with respect to  $V_{read}$ , desired threshold voltage distribution can be attained. A variation in the threshold voltage

distribution at the program time of the cell transistor is shown in FIG. 4.

In FIG. 4, if a program characteristic variation of the cell transistor is  $W_{vt}$ , the following conditions must be satisfied in order to attain desired threshold voltage distribution.

- First program WL potential: the cell which is programmed at the highest speed is not programmed with voltage equal to or higher than  $V_{verify} + \Delta V_{pgm}$ .

- Last program WL potential: the cell which is programmed at the lowest speed is programmed with voltage equal to or higher than  $V_{verify}$ .

During the program operation, it is necessary to increase the program WL potential by the unit of  $\Delta V_{pgm}$ , and if the number of program operations to perform the program operations for all of the cell transistors is  $N_{loop}$ , then  $N_{loop}$  is expressed as follows.

$$N_{loop} \geq W_{vt} / \Delta V_{pgm}$$

As indicated by the above expression, the number  $N_{loop}$  of program operations becomes larger as the program characteristic variation  $W_{vt}$  of the cell transistor becomes larger. The program characteristic variation  $W_{vt}$  becomes larger as the device is further miniaturized. Therefore, there will occur a problem that the program speed is lowered with the development of miniaturization.

Further, the number  $N_{loop}$  of program operations

decreases with a reduction of  $\Delta V_{pgm}$ . If  $\Delta V_{pgm}$  is reduced, the threshold voltage distribution range of the cell transistor can be finely and precisely controlled. This technique is useful for a multi-value memory and a reduction in the readout potential  $V_{read}$ , for example. For example, the multi-value memory has an order of plural data items in a potential range equal to or lower than the readout potential  $V_{read}$ . Therefore, it is necessary to more finely and precisely control the threshold voltage distribution range of the cell transistors in the multi-value memory in comparison with a binary memory. If an attempt is thus made to finely and precisely control the threshold voltage distribution range of the cell transistors, the number  $N_{loop}$  of program operations increases and the program speed is lowered.

Document 1: Jpn. Pat. Appln. KOKAI Publication  
No. 7-169284

Document 2: U.S. Patent Specification  
No. 5,555,204

Document 3: G. J. Hemink, T. Tanaka, T. Endoh, S. Aritome, and R. Shirota, "Fast and accurate programming method for multilevel NAND flash EEPROM's", in SYMP. VLSI Technology Dig. Tech. Papers, June 1995, pp. 129-130.

#### BRIEF SUMMARY OF THE INVENTION

A nonvolatile semiconductor memory device

according to a first aspect of the present invention comprises a plurality of wirings formed to extend in a first direction; memory cells containing nonvolatile memory cell transistors and connected to the plurality  
5 of wirings; word lines commonly connected to gate electrodes of the nonvolatile memory cell transistors arranged along a second direction which intersects the first direction; and driving circuits respectively connected to the plurality of wirings, each of the  
10 driving circuits including a detection circuit which detects threshold voltage of the nonvolatile memory cell transistor in a verify operation, a storage circuit which stores threshold voltage detected by the detection circuit and a potential setting circuit which  
15 sets potential of the wiring to at least three potentials in a program operation following the verify operation based on the threshold voltage stored in the storage circuit.

A data programming method of a nonvolatile  
20 semiconductor memory device according to a second aspect of the present invention comprises programming data into a nonvolatile memory cell transistor, verifying threshold voltage of the nonvolatile memory cell transistor into which data has been programmed,  
25 setting potential of a bit line to program inhibition potential used to inhibit data programming if it is detected based on the result of verification that a



sufficient amount of data has been programmed, and setting the potential of the bit line to at least one program suppression potential which lies between the program inhibition potential and the program potential and is used to program data while suppressing a program amount or program potential used to program data according to the threshold voltage of the nonvolatile memory cell transistor and additionally programming data into the nonvolatile memory cell transistor if it is detected based on the result of verification that a sufficient amount of data has not been programmed.

#### BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

FIG. 1 is a block diagram showing a nonvolatile semiconductor memory device according to a typical (conventional) example.

FIG. 2 is a flow diagram showing the verify operation which the nonvolatile semiconductor memory device according to the typical example performs.

FIG. 3 is an operation waveform diagram showing operation waveforms of the nonvolatile semiconductor memory device according to the typical example.

FIG. 4 is a diagram showing the threshold voltage distributions before and after the verify operation.

FIGS. 5A, 5B, 5C and 5D are diagrams showing one example of a potential control operation which a nonvolatile semiconductor memory device according to a first embodiment of this invention performs.

FIG. 6 is a flow diagram showing a first example of a verify operation which the nonvolatile semiconductor memory device according to the first embodiment of this invention performs.

5        FIG. 7 is an operation waveform diagram showing a first example of operation waveforms of the nonvolatile semiconductor memory device according to the first embodiment of this invention.

10        FIG. 8 is a flow diagram showing a second example of the verify operation which the nonvolatile semiconductor memory device according to the first embodiment of this invention performs.

15        FIG. 9 is an operation waveform diagram showing a second example of the operation waveforms of the nonvolatile semiconductor memory device according to the first embodiment of this invention.

FIG. 10 is a diagram showing a program operation in the first embodiment of this invention in comparison with a typical program operation.

20        FIG. 11 is a diagram showing the relation between bit line potential VBL at the readout time and time.

FIG. 12 is a diagram showing one example of a verify method which a nonvolatile semiconductor memory device according to a second embodiment of this invention performs.

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FIG. 13 is a diagram showing the relation between discharging time and bit line potential at the program

time of the nonvolatile semiconductor memory device according to the second embodiment of this invention.

FIG. 14 is a diagram showing one example of a verify method which a nonvolatile semiconductor memory device according to a third embodiment of this invention performs.

FIG. 15 is a diagram showing the relation between bit line potential at the program time of the nonvolatile semiconductor memory device according to the third embodiment of this invention and bit line potential after discharging.

FIG. 16 is a block diagram showing a nonvolatile semiconductor memory device according to a fourth embodiment of this invention.

FIG. 17 is a block diagram showing an illustrative internal structure of a memory card in accordance with an embodiment of the present invention.

FIG. 18 is a block diagram showing an illustrative internal structure of a memory card in accordance with an embodiment of the present invention.

FIG. 19 is an illustrative example of cardholder and a memory card in accordance with an embodiment of the present invention.

FIG. 20 shows a connecting apparatus operable to receive a memory card or cardholder.

FIG. 21 is an illustrative example of a connecting apparatus connected to a personal computer via a

connecting wire and having a memory card inserted therein.

FIG. 22 shows an IC card in accordance with an embodiment of the present invention.

5        FIG. 23 is a block diagram of an IC card in accordance with an embodiment of the present invention.

FIG. 24 is a block diagram showing a nonvolatile semiconductor memory device to which this invention can be applied.

10                    DETAILED DESCRIPTION OF THE INVENTION

There will now be described embodiments of this invention with reference to the accompanying drawings. When explaining this invention, common portions are denoted by the same reference symbols throughout the drawings.

15                    (First Embodiment)

First, the program operation which a nonvolatile semiconductor memory device according to a first embodiment of this invention performs is explained.

20        FIGS. 5A to 5D are diagrams showing one example of a potential control operation which the nonvolatile semiconductor memory device according to the first embodiment of this invention performs at the program operation time.

25        FIG. 5A shows a case wherein program potential (VBLpgm) is applied to a bit line BL and program gate potential (Vpgm) is applied to a word line WL to

program data into a selected cell transistor (which is hereinafter referred to as a selected cell). At this time,  $V_{BLpgm}$  is set sufficiently lower than the gate potential ( $V_{sg}$ ) of a selection transistor SG1 on the bit line side. Therefore, the selection transistor SG1 is set into the ON state to lower the channel potential of the selected cell to  $V_{BLpgm}$  and data is programmed into the selected cell until threshold voltage determined by  $V_{pgm}$  can be attained. Next, after the threshold voltage of the selected cell is verified by the verify operation, the potential of the word line WL is increased by a preset amount ( $\Delta V_{pgm} \times 2$ ) and a next program operation is started. In the first embodiment, three states are selectively set as the program state in the next program operation.

(i) Program state

The program potential  $V_{BLpgm}$  is applied to the bit line BL and stepped-up program gate potential  $V_{pgm} + (\Delta V_{pgm} \times 2)$  is applied to the word line WL. In this case, the same program operation as in the preceding cycle is performed with respect to the selected cell and the threshold voltage thereof is increased by an increased amount of the word line potential, that is,  $\Delta V_{pgm} \times 2$ . The state is shown in FIG. 5B.

(ii) Program suppression state

Program suppression potential  $V_{BLpgm} + \Delta V_{pgm}$  is applied to the bit line BL and the stepped-up program

gate potential  $V_{pgm} + (\Delta V_{pgm} \times 2)$  is applied to the word line WL. At this time,  $V_{BLpgm} + \Delta V_{pgm}$  and  $V_{sg}$  are set so as to set the selection transistor SG1 on the bit line side into the sufficient ON state. In this case, the  
5 program operation is performed for the selected cell and potential which is higher than that in the case (i) by  $\Delta V_{pgm} \times 2 - \Delta V_{pgm} = \Delta V_{pgm}$  is transferred to the channel of the selected cell. Therefore, an amount of  $\Delta V_{pgm}$  among the increased amount of  $\Delta V_{pgm} \times 2$  of the word line  
10 potential is cancelled, and as a result, the threshold voltage of the selected cell is increased by  $\Delta V_{pgm}$ . The state is shown in FIG. 5C.

(iii) Program inhibition state

Program inhibition potential  $V_{BLinhibit}$  is applied  
15 to the bit line BL and the stepped-up program gate potential  $V_{pgm} + (\Delta V_{pgm} \times 2)$  is applied to the word line WL. At this time, the selection transistor SG1 on the bit line side is set into the OFF state, the channel potential of the selected cell is not lowered and the  
20 program operation is not performed. As a result, the threshold voltage of the selected cell is not increased. The state is shown in FIG. 5D.

By selectively setting the three program states (i) to (iii), three results of " $\Delta V_{pgm} \times 2$ ", " $\Delta V_{pgm}$ ", "no  
25 increase" can be expected with respect to an increase in the threshold voltage of the selected cell.

Next, a first example of the verify operation

performed during the above program operation is explained. FIG. 6 is a flow diagram showing a first example of a verify operation which the nonvolatile semiconductor memory device according to the first  
5 embodiment performs.

As shown in FIG. 6, first, the potential of the word line WL is set to  $V_{pgm}$  and data is programmed into a selected cell (ST.1).

Assume that the lowest threshold voltage which the  
10 selected cell must satisfy after the end of the program operation is  $V_{verify}$ . In this case, the potential of the word line WL is set to  $(V_{verify} - \Delta V_{pgm})$  and data is read out from the selected cell (ST.2: verify 1). Assume that the selected cell is turned ON and the  
15 potential of the bit line BL is lowered as the result of readout. Cells which cause the potential of the bit line BL to be lowered are classified into an "A" group (if NG). The threshold voltage of the cell in the "A" group is lower than  $(V_{verify} - \Delta V_{pgm})$ .

20 Next, the potential of the word line WL is set to  $V_{verify}$  and data is read out from the selected cell (ST.3: verify 2). At this time, a current flows in the selected cell and cells which cause the potential of the bit line BL to be lowered and are not contained in  
25 the "A" group are classified into a "B" group (if NG). The threshold voltage of the cell in the "B" group is higher than  $(V_{verify} - \Delta V_{pgm})$  and lower than  $V_{verify}$ .

Remaining cells which are not contained in the "A" and "B" groups are classified into a "C" group. The threshold voltage of the cell in the "C" group is equal to or higher than  $V_{verify}$ . After this, the potential of the word line WL is increased by  $\Delta V_{pgm} \times 2$  and an additional program operation is performed (ST.4: additional program). At the time of additional program, the cells in the "A", "B", "C" groups are respectively set to correspond to the states (i), (ii), (iii). The states before and after the additional program operation are summarized as follows.

"A" group ... (i) Program state:

- The threshold voltage before the additional program operation is not higher than  $(V_{verify} - \Delta V_{pgm})$
- An increase in the threshold voltage during the additional program operation is  $\Delta V_{pgm} \times 2$
- The threshold voltage after the additional program operation is not higher than  $(V_{verify} + \Delta V_{pgm})$
- The threshold voltage range which can be controlled in the additional program operation is  $\Delta V_{pgm} \times 2$

"B" group ... (ii) Program suppression state:

- The threshold voltage before the additional program operation is equal to or higher than  $(V_{verify} - \Delta V_{pgm})$  and lower than  $V_{verify}$
- An increase in the threshold voltage during the additional program operation is  $\Delta V_{pgm}$



- The threshold voltage after the additional program operation is equal to or higher than  $V_{verify}$  and equal to or lower than  $(V_{verify} + \Delta V_{pgm})$

- The threshold voltage range which can be controlled in the additional program operation is  $\Delta V_{pgm}$

"C" group ... (iii) Program inhibition state:

- The threshold voltage before the additional program operation is equal to or higher than  $V_{verify}$
- There is no increase in the threshold voltage during the additional program operation
- The threshold voltage after the additional program operation is maintained in the state set before the additional program operation

Examples of operation waveforms according to the potential control operation at the program operation time and the verify operation in the first example are shown in FIG. 7.

Next, a second example of the verify operation is explained. FIG. 8 is a flow diagram showing a second example of the verify operation which the nonvolatile semiconductor memory device according to the first embodiment performs. In the first example, the three program states (i) to (iii) are determined by setting the potential of the word line WL to  $(V_{verify} - \Delta V_{pgm})$  to perform the verify operation and then setting the potential of the word line WL to  $V_{verify}$  to perform the verify operation again. The three program states (i)

to (iii) can also be determined by setting the potential of the word line WL to Vverify to perform the verify operation and then setting the potential of the word line WL to  $(V_{verify} - \Delta V_{pgm})$  to perform the verify operation again. The second example corresponds to the latter case.

As shown in FIG. 8, first, the potential of the word line WL is set to  $V_{pgm}$  and data is programmed into a selected cell (ST.1).

After the end of the program operation, the potential of the word line WL is set to Vverify and data is read out from the selected cell (ST.2: verify 1). As the result of readout, if the selected cell is turned OFF to prevent the bit line BL from being discharged, it is determined that the threshold voltage before the additional program operation is equal to or higher than Vverify (if OK). Then, the potential of the bit line BL is set to  $V_{BLinhibit}$  (ST.3: end of program operation). If the selected cell is turned ON and the bit line BL is discharged, the potential of the bit line BL is set depending on the result of the next readout operation (if NG).

Next, the potential of the word line WL is set to  $(V_{verify} - \Delta V_{pgm})$  and data is read out from the selected cell (ST.4: verify 2). As the result of readout, if the selected cell is turned OFF to prevent the bit line BL from being discharged, it is determined that the

threshold voltage before the additional program operation is equal to or higher than  $(V_{\text{verify}} - \Delta V_{\text{pgm}})$  and lower than  $V_{\text{verify}}$  (if OK). Then, the potential of the bit line BL is set to  $(V_{\text{BLpgm}} + \Delta V_{\text{pgm}})$  (ST.5: to  
5 program suppression state). If the selected cell is turned ON and the bit line BL is discharged, it is determined that the threshold voltage before the additional program operation is equal to or lower than  $(V_{\text{verify}} - \Delta V_{\text{pgm}})$  (if NG) and the potential of the bit  
10 line BL is set to  $V_{\text{BLpgm}}$  (ST.6: to program state). After this, the potential of the word line WL is increased by  $\Delta V_{\text{pgm}} \times 2$  and the additional program operation is performed (ST.7: additional program).

Examples of operation waveforms according to the  
15 potential control operation at the program operation time and the verify operation in the second example are shown in FIG. 9.

The following advantages can be attained according to the nonvolatile semiconductor memory device  
20 according to the first embodiment. Assume that time required for programming is  $T_{\text{pgm}}$  and time required for verifying is  $T_{\text{verify}}$ . Further, assume that the above times contain all of times required for actually generating operation pulses, for example, time required  
25 for stably setting potentials and time required for restoring nodes to which potentials are applied at the program operation time or verify operation time to the

initial state. As shown in FIG. 10, when the typical example (conventional case) and the first embodiment (proposed case) are compared with each other, the number of program (write) operations performed until program potential is increased by  $\Delta V_{pgm} \times 2$  is reduced by one time in the first embodiment. Therefore, time for increasing the program potential by  $\Delta V_{pgm} \times 2$  is reduced by  $T_{pgm}$  in comparison with the case of the typical example. As a result, the high-speed program operation can be attained. Further, since the program suppression potential is set in order to perform the potential control operation at the program time, the controllable threshold voltage range is set not to  $\Delta V_{pgm} \times 2$  but to  $\Delta V_{pgm}$ . Therefore, the control operation for the threshold voltage range can be performed with substantially the same high precision as in the case of the typical example. In addition, since the potential control operation is independently performed for each bit line BL, the threshold voltage distribution range control operation can be performed with high precision for each of the cell transistors.

The verify operation is explained more in detail below. The verify operation mainly contains five time periods, that is, word line potential setting time, bit line precharge time, bit line discharging time, bit line potential sense time and potential restoring time. In the operation waveform diagram of FIG. 9

corresponding to a second example of the verify operation, the verify operation contains two independent readout operations. However, the verify operation can also be performed as a series of readout operations to change only the word line potential after the elapse of the bit line potential sense time and additionally discharge the bit line by adequately setting the word line potential setting time and bit line discharging time. This is shown in FIG. 7 which is based on the first example of the verify operation. Therefore, in the first example of the verify operation, the numbers of bit line precharge times and potential restoring times can each be reduced by one time in comparison with the second example of the verify operation and the advantage that the higher speed operation can be performed can be obtained.

Further, in the program suppression state, only if the condition that the selection gate SG1 is sufficiently turned ON is satisfied, the bit line potential can be further raised. Therefore, for example, the following four states can be selected as the program state in a case where it is desired to increase the word line potential for every  $\Delta V_{pgm} \times 3$  at the additional program time.

- 25 (i) Program state
  - Bit line potential =  $V_{BLpgm}$
- (ii) Program suppression state 1

- Bit line potential =  $VBL_{pgm} + \Delta V_{pgm}$
- (iii) Program suppression state 2
- Bit line potential =  $VBL_{pgm} + \Delta V_{pgm} \times 2$
- (iv) Program inhibition state
- 5       • Bit line potential =  $VBL_{inhibit}$

In order to determine the four program states (i) to (iv), the three readout operations may be performed by using three potentials applied to the word line WL which are respectively set to  $(V_{verify} - \Delta V_{pgm} \times 2)$ ,  
10        $(V_{verify} - \Delta V_{pgm})$  and  $V_{verify}$ , for example. In this case, time for raising the program potential by  $\Delta V_{pgm} \times 3$  can be reduced by  $T_{pgm} \times 2$  in comparison with the case of the typical example while the controlled threshold voltage range is kept at substantially the same value  
15       as in the typical example case.

Likewise, when it is desired to increase the word line potential for every  $\Delta V_{pgm} \times n$  at the additional program time, the following  $(n+1)$  states can be selected as the program state. In this case,  $n$  is an  
20       integer equal to or larger than "1".

- (i) Program state
- Bit line potential =  $VBL_{pgm}$
- (ii) Program suppression state 1
- Bit line potential =  $VBL_{pgm} + \Delta V_{pgm}$
- 25       (iii) Program suppression state 2
- Bit line potential =  $VBL_{pgm} + \Delta V_{pgm} \times 2$

...

(n) Program suppression state (n-1)

- Bit line potential =  $VBL_{pgm} + \Delta V_{pgm} \times (n-1)$

(n+1) Program inhibition state

- Bit line potential =  $VBL_{inhibit}$

5           In order to determine the (n+1) program states (i) to (n+1), the n readout operations in total may be performed by using n potentials applied to the word line WL which are respectively set to ( $V_{verify} - \Delta V_{pgm} \times (n-1)$ ), ( $V_{verify} - \Delta V_{pgm} \times (n-2)$ ), ..., ( $V_{verify} - \Delta V_{pgm} \times 2$ ), ( $V_{verify} - \Delta V_{pgm}$ ) and  $V_{verify}$ , for example. In  
10           this case, time for raising the program potential by  $\Delta V_{pgm} \times n$  can be reduced by  $T_{pgm} \times (n-1)$  in comparison with the case of the typical example while the controlled threshold voltage range is kept at substantially the  
15           same value as in the typical example case.

          As described above, according to the first embodiment, in a memory in which discrete potentials can be set for the bit line at the program time, a high-speed program operation can be performed while  
20           suppressing a lowering in the control precision for the threshold voltage to a minimum by performing the verify readout operation which is adequately set for each case and determining the bit line potential at the next program time based on the result of the verify readout  
25           operation. Alternatively, the threshold voltage control precision can be enhanced while suppressing a lowering in the program speed to a minimum.

The upper limit of the bit line potential at the program time in the first embodiment is set on a condition that the selection gate SG1 is sufficiently turned ON. Therefore, when  $\Delta V_{pgm}$  is small, for example, when the threshold voltage control operation with high precision is required as in the multi-value memory, the advantage thereof can be more effectively attained.

In the first embodiment, a case wherein the minimum amount of a variation in the word line potential at the verify time is the same as the minimum amount of a variation in the bit line potential at the program time is explained. However, it is clearly understood that the threshold voltage control operation according to the present invention can be realized even when a verify method different from the above-described readout method is used if an adequate calibration method is defined and it is set in one-to-one correspondence to the threshold voltage which is suppressed by a rise in the bit line potential at the program time.

The threshold voltage of a selected cell can be detected by changing potential applied to the gate electrode of the selected cell in the verify operation. In addition, for example, the threshold voltage of a selected cell can be detected by changing at least one of determination reference time to determine the bit



line potential, determination reference potential to  
determine the bit line potential, and initial charge  
potential applied to the bit line in the verify  
operation and then performing the verify readout  
5 operation two times or more. Further, the above verify  
methods can be variously combined.

For example, when it becomes necessary to use  
negative word line potential as verify potential, a  
method for performing the readout operation by applying  
10 positive bias to the common source line or the  
substrate in which the cell transistors are formed is  
generally used. However, in this case, a plurality of  
verify methods can be adequately combined based on the  
condition of the necessary word line potentials or the  
15 like.

(Second Embodiment)

FIG. 11 is a diagram showing the transition with  
time of a cell current flowing in a selected cell at  
the readout time. A selected bit line BL is raised to  
20 preset potential and a selection gate and non-selected  
word lines WL are turned ON. At this time, potential  
corresponding to threshold voltage which is required to  
be determined is applied to a selected word line WL.  
In the case of a verify operation, the lowest threshold  
25 voltage which the selected cell must satisfy, that is,  
V<sub>verify</sub> may be applied in some cases. However, it is  
also possible to apply potential which can be used to

calculate the threshold voltage of the selected cell with the highest precision based on the cell transistor characteristic or the like. When the threshold voltage of the selected cell is lower than  $V_{verify}$ , a cell  
5 current flows to lower the potential of the bit line. On the other hand, when the threshold voltage of the selected cell is higher than  $V_{verify}$ , no cell current flows and the bit line potential is kept at the high level. Even if the threshold voltage of the selected  
10 cell is lower than  $V_{verify}$ , a cell current decreases according to the current characteristic of the cell transistor as the threshold voltage of the selected cell comes nearer to  $V_{verify}$ . The transition of the bit line potential with time occurs based on a  
15 transition characteristic of discharging the bit line capacitor by use of a cell current. Therefore, the bit line potential is lowered in a shorter period of time as the cell current is larger and it takes a longer time for the bit line potential to be lowered as the  
20 cell current is smaller.

The verify method using the above characteristic is shown in FIG. 12. FIG. 12 shows the transition of a cell current with time in a case where the threshold voltage is set to  $(V_{verify} - \Delta V_{pgm} \times 4)$ ,  $(V_{verify} - \Delta V_{pgm} \times 3)$ ,  
25  $(V_{verify} - \Delta V_{pgm} \times 2)$ ,  $(V_{verify} - \Delta V_{pgm} \times 1)$ ,  $V_{verify}$ . A circuit which stores a period of time (discharge time) in which the bit line potential is lower than preset

potential Vsense is connected to the bit line BL.  
Discharge times when the above threshold voltages are  
used are set to Tsense1, Tsense2, Tsense3, Tsense4,  
Tsense5. Since the cell current is set in one-to-one  
5 correspondence to the discharge characteristic of the  
bit line, it is possible to calculate the threshold  
voltage of the selected cell based on the discharge  
time. Therefore, the high-speed program operation can  
be performed while suppressing a reduction in the  
10 threshold voltage control precision to a minimum by  
detecting the discharge time and reflecting the same on  
the bit line potential at the program time. One  
example of a combination of the discharge time, the  
threshold voltage of the selected cell and the bit line  
15 potential at the program time is shown in Table 1.

Table 1

Discharge time	Calculated threshold voltage	BL potential at program time	Threshold voltage after program
Tsense1	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 4$	$V_{\text{BLpgm}}$	$V_{\text{verify}}$
Tsense2	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 3$	$V_{\text{BLpgm}} + \Delta V_{\text{pgm}} \times 1$	$V_{\text{verify}}$
Tsense3	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 2$	$V_{\text{BLpgm}} + \Delta V_{\text{pgm}} \times 2$	$V_{\text{verify}}$
Tsense4	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 1$	$V_{\text{BLpgm}} + \Delta V_{\text{pgm}} \times 3$	$V_{\text{verify}}$
Tsense5	$V_{\text{verify}}$	$V_{\text{BLinhibit}}$	$V_{\text{verify}}$

\* For programming, potential which is higher than  
20 program potential used before the verify operation by

$\Delta V_{pgm} \times 4$  is used

The relation between the discharge time in the second embodiment and the bit line potential at the program time is shown in FIG. 13. The example shown in Table 1 is indicated by circles in FIG. 13. If the discharge time is recorded by use of successive values and successive potentials are set as the bit line potential at the program time, the threshold voltage distribution range after the program operation can be set limitlessly closer to "0". The bit line potential at this time is defined by a straight line in FIG. 13. If the discharge time is shorter than  $T_{sense1}$ , the threshold voltage of the selected cell is excessively low so that  $V_{BLpgm}$  will be applied to the bit line to set the program state. If the discharge time is longer than  $T_{sense5}$ , the threshold voltage of the selected cell exceeds  $V_{verify}$  so that  $V_{BLinhibit}$  will be applied to the bit line to set the program inhibition state.

(Third Embodiment)

A third embodiment utilizing another verify method is shown in FIG. 14. FIG. 14 is a diagram showing the transition with time of a cell current flowing in a selected cell at the readout time. The third embodiment is different from the second embodiment in the following point. In the second embodiment, the threshold voltage of the selected cell is detected based on a period of time in which the bit line

potential reaches the preset potential  $V_{sense}$  in the verify operation. In the third embodiment, the threshold voltage of the selected cell is detected based on bit line potential when preset time  $T_{sense}$  has elapsed in the verify operation. FIG. 14 shows the transition of a cell current with time in a case where the threshold voltage is set to  $(V_{verify} - \Delta V_{pgm} \times 4)$ ,  $(V_{verify} - \Delta V_{pgm} \times 3)$ ,  $(V_{verify} - \Delta V_{pgm} \times 2)$ ,  $(V_{verify} - \Delta V_{pgm} \times 1)$ ,  $V_{verify}$ . A circuit which stores the bit line potential when the preset time  $T_{sense}$  has elapsed is connected to the bit line BL. Bit line potentials after discharging for the above respective threshold voltages are set to  $V_{sense1}$ ,  $V_{sense2}$ ,  $V_{sense3}$ ,  $V_{sense4}$ ,  $V_{sense5}$ . Since the cell current is set in one-to-one correspondence to the discharge characteristic of the bit line, it is possible to calculate the threshold voltage of the selected cell based on the bit line potential after discharging. Therefore, the high-speed program operation can be performed while suppressing a reduction in the threshold voltage control precision to a minimum by measuring the bit line potential after discharging and reflecting the same on the bit line potential at the program time. One example of a combination of the bit line potential after discharging, the threshold voltage of the selected cell and the bit line potential at the program time is shown in Table 2.

Table 2

BL potential after discharging	Calculated threshold voltage	BL potential at program time	Threshold voltage after program
Vsense1	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 4$	$V_{\text{BLpgm}}$	$V_{\text{verify}}$
Vsense2	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 3$	$V_{\text{BLpgm}} + \Delta V_{\text{pgm}} \times 1$	$V_{\text{verify}}$
Vsense3	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 2$	$V_{\text{BLpgm}} + \Delta V_{\text{pgm}} \times 2$	$V_{\text{verify}}$
Vsense4	$V_{\text{verify}} - \Delta V_{\text{pgm}} \times 1$	$V_{\text{BLpgm}} + \Delta V_{\text{pgm}} \times 3$	$V_{\text{verify}}$
Vsense5	$V_{\text{verify}}$	$V_{\text{BLinhibit}}$	$V_{\text{verify}}$

5        \* For programming, potential which is higher than  
program potential used before the verify operation by  
 $\Delta V_{\text{pgm}} \times 4$  is used

      The relation between the bit line potential after  
discharging in the third embodiment and the bit line  
10        potential at the program time is shown in FIG. 15. The  
example shown in Table 2 is indicated by circles in  
FIG. 15. If the bit line potential after discharging  
is recorded by use of successive values and successive  
potentials are set as the bit line potential at the  
15        program time, the threshold voltage distribution range  
after the program operation can be set limitlessly  
closer to "0". The bit line potential at this time is  
defined by a straight line in FIG. 15. If the bit line  
potential after discharging is lower than Vsense1, the  
20        threshold voltage of the selected cell is excessively

low so that VBLpgm will be applied to the bit line to set the program state. If the bit line potential after discharging is higher than Vsense5, the threshold voltage of the selected cell exceeds Vverify so that  
5 VBLinhibit will be applied to the bit line to set the program inhibition state.

(Fourth Embodiment)

As a fourth embodiment, one example of the device configuration of a nonvolatile semiconductor memory  
10 device which can be applied to the first to third embodiments is explained below.

FIG. 16 is a block diagram showing a nonvolatile semiconductor memory device according to the fourth embodiment of this invention.

15 As shown in FIG. 16, a plurality of bit lines BL (BLk-1 to BL-k+1) are formed along respective columns. Memory cells each including nonvolatile memory cell transistors MC are connected to the respective bit lines BL. In this example, a NAND cell is used as one  
20 example of the memory cell. The gate electrodes of the cell transistors MC arranged on each row which intersects the column are commonly connected to a corresponding one of word lines WL (WL1 to WL8). The bit lines BL are respectively connected to charging  
25 circuits 1 which supply initial charging potentials, for example, readout potentials (VBLread) at the data readout time and bit line driving circuits 2. For

example, the charging circuits 1 are each supplied with a readout control signal Sread. The charging circuit 1 charges the bit line BL to the initial charging potential according to the control signal Sread.

5 Therefore, data items are simultaneously read out from the plurality of memory cells MC connected to one word line WL. The driving circuit 2 includes a detection circuit (detection CKT) 21, storage circuit (storage CKT) 22 and potential setting circuit 23. For example,  
10 the detection circuit 21 detects the threshold voltage of the cell transistor in the program verify operation. One concrete example of the detection circuit 21 is a sense amplifier. The storage circuit 22 stores the threshold voltage detected by the detection circuit 21.  
15 One concrete example of the storage circuit 22 is a data latch circuit. The storage circuit 22 stores the results of the verify readout operation which is performed two times or more in the case of the first embodiment, a period of time in which the potential of  
20 the bit line BL has reached the preset potential Vsense in the case of the second embodiment, and the potential of the bit line BL when the preset time Tsense has elapsed in the case of the third embodiment. Thus, the storage circuit 22 stores the threshold value of the  
25 selected cell. The potential setting circuit 23 sets the potential of the bit line BL to program inhibition potential VBLinhibit used to inhibit the data



programming operation, program potential  $VBL_{pgm}$  used to permit the data programming operation, and program suppression potential  $VBL_{pgm} + \Delta V_{pgm}$  which has potential between  $VBL_{inhibit}$  and  $VBL_{pgm}$  and is used to program data while suppressing a program amount based on the threshold value stored in the storage circuit 22 in the program operation which follows the program verify operation. For example, if the nonvolatile semiconductor memory device is formed with the above configuration, the potential control operation and verify operation explained in the first to third embodiments can be realized. In FIG. 16, a state in which the bit line  $BLk-1$  is set to  $VBL_{inhibit}$  ( $V3$ ), the bit line  $BLk$  is set to  $VBL_{pgm}$  ( $V1$ ), and the bit line  $BLk+1$  is set to  $VBL_{pgm} + \Delta V_{pgm}$  ( $V2$ ) is shown.

(Fifth Embodiment)

One application example in which the nonvolatile semiconductor memory device explained in the above embodiment is used is explained as a fifth embodiment. In one example, shown in FIG. 17, a memory card 60 includes the semiconductor memory device 50. As shown in FIG. 17, the memory card 60 is operable to receive/output predetermined signals and data from/to an external device (not shown). A signal line (DAT), a command line enable signal line (CLE), an address line enable signal line (ALE) and a ready/busy signal line (R/B) are connected to the

memory card 60 having the semiconductor memory device  
50. The signal line (DAT) transfers data, address or  
command signals. The command line enable signal line  
(CLE) transfers a signal, which indicates that a  
5 command signal is transferred on the signal line (DAT).  
The address line enable signal line (ALE) transfers a  
signal, which indicates that an address signal is  
transferred on the signal line (DAT). The ready/busy  
signal line (R/B) transfers a signal, which indicates  
10 whether the memory device 50 is ready, or not.

Another exemplary implementation is shown in FIG.  
18. The memory card shown in FIG. 18 differs from the  
memory card presented in FIG. 17 in that the memory  
card 60 of FIG. 18 includes, in addition to the memory  
15 device 50, a controller 70 which controls the  
semiconductor memory device 50 and receives/transfers  
predetermined signals from/to an external device (not  
shown).

The controller 70 includes interface units (I/F)  
20 71, 72, a microprocessor unit (MPU) 73, a buffer RAM 74  
and an error correction code unit (ECC) 75. The  
interface unit (I/F) 71, 72 receives/outputs  
predetermined signals from/to an external device (not  
shown) and the semiconductor memory device 50,  
25 respectively. The microprocessor unit 73 converts a  
logical address into a physical address. The buffer  
RAM 74 stores data temporarily. The error correction

code unit 75 generates an error correction code. A  
command signal line (CMD), a clock signal line (CLK)  
and a signal line (DAT) are connected to the memory  
card 60. It should be noted that the number of the  
5 control signal lines, bit width of the signal line  
(DAT) and a circuit construction of the controller 70  
could be modified suitably.

Another exemplary implementation is shown in FIG.  
19. As can be seen from FIG. 19, a memory cardholder  
10 80 is provided for receiving a memory card 60 having a  
memory device 50. The cardholder 80 is connected to an  
electronic device (not shown) and is operable as an  
interface between the card 60 and the electronic  
device. The cardholder 80 may perform one or more of  
15 the functions of the controller 70 described in  
connection with FIG.18.

Another exemplary implementation will be explained  
with reference to FIG. 20. FIG. 20 shows a connecting  
apparatus operable to receive a memory card or a  
20 cardholder, either of which includes the memory device.  
The memory card or cardholder is insertable in the  
connecting apparatus 90 and is electrically connectable  
to the apparatus. The connecting apparatus 90 is  
connected to a board 91 via a connecting wire 92 and an  
25 interface circuit 93. The board 91 contains a CPU  
(Central Processing Unit) 94 and a bus 95.

Another exemplary implementation is shown in FIG.

21. As shown in FIG. 21, a memory card 60 or a  
cardholder 80, either of which includes the memory  
device, is inserted and electrically connectable to a  
connecting apparatus 90. The connecting apparatus 90  
5 is connected to a PC (Personal Computer) 300 via  
connecting wire 92.

Another exemplary implementation is shown in FIGS.  
22 and 23. As shown in FIGS. 22 and 23, a  
semiconductor memory device 50 and other circuits such  
10 as ROM (read only memory) 410, RAM (random access  
memory) 420 and CPU (central processing unit) 430 are  
included in an IC (interface circuit) card 500. The IC  
card 500 is connectable to an external device via a  
plane terminal 600 that is coupled to an MPU (micro-  
15 processing unit) portion 400 of the card 450. The CPU  
430 contains a calculation section 431 and a control  
section 432, the control section 432 being coupled to  
the memory device 50, the ROM 410 and the RAM 420.  
Preferably, the MPU 400 is molded on one surface of the  
20 card 500 and the plane connecting terminal 600 is  
formed on the other surface.

As described above, according to the nonvolatile  
semiconductor memory device of the above embodiments,  
the high-speed program operation can be performed  
25 without lowering the control precision of the threshold  
voltage of the memory cell by separately controlling  
the bit line potentials according to the result of the

program verify operation.

Further, this invention is not limited to the above embodiments and can be variously modified without departing from the technical scope thereof when realizing the embodiments. For example, in the above  
5       embodiments, a NAND cell is used as an example of the memory cell, but the application of this invention is not limited to the NAND nonvolatile semiconductor memory device containing the NAND cells. For example,  
10       as shown in FIG. 24, this invention can be applied to an AND nonvolatile semiconductor memory device containing AND cells and a nonvolatile semiconductor memory device of a type other than the NAND type and AND type.

15       Further, the above embodiments can be independently realized, but it is also possible to adequately combine the embodiments.

Further, inventions of various stages are contained in the above embodiments and can be extracted  
20       by adequately combining a plurality of constituent elements disclosed in the respective embodiments.

In the above embodiments, a case wherein the present invention is applied to the nonvolatile semiconductor memory device is explained, but a  
25       semiconductor integrated circuit device such as a processor, system LSI which contains the nonvolatile semiconductor memory device can be included within the

scope of this invention.

Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to  
5 the specific details and representative embodiments shown and described herein. Accordingly, various modifications may be made without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.